SCHOLAR Tutor Handbook

Unit 3: Electromagnetism

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Contents

1 Electric force and field 1

2 Electric potential 3

3 Motion in an electric field 5

4 Magnetic fields 7

5 Capacitors 11

6 Inductors 13

7 Electromagnetic radiation 17

Topic 1

Electric force and field

1.1 Introduction

Teachers who have taught the Traditional Advanced Higher should be comfortable with this first Topic in the Electromagnetism Unit since it is identical to the first topic in the old Electrical Phenomena Unit.

It is worth noting that there are several opportunities for students to perform practical work related to this Topic.

1.2 Electric charge

This short section introduces the concept of charge, the unit of charge, the coulomb, and the fundamental charge carried on an electron.

1.3 Coulomb's law

Students should be able to apply Coulomb's inverse square law for the force between two point charges $F = \frac{Q_1\,Q_2}{4\pi\varepsilon_0 r^2}$.

Students do not need to be able to describe the principles of a method for verifying Coulomb's law, however this could be an opportunity to carry out experimental work if suitable equipment is available.

1.3.2 Force between more than two point charges

Activity: Three charged particles in a line

This Activity asks students to plot the force acting on a test charge as it is moved along the straight line between two charged objects, one positive and the other negative. The separate forces from each of the charges could be plotted individually, and the sum then plotted. Students should be encouraged to think about what would happen if the two objects had the same sign charge, and if this would be the same or opposite to the sign of the test charge.

1.4 Electric field strength

The remainder of this Topic deals with the concept of the electric field.

Students should be able to state that the expression for the electric field strength E at a distance r from a point charge Q is $E = \frac{Q}{4\pi\varepsilon_0 r^2}$.

Although the derivation of this expression from the definition of the electric field is given in the notes, this derivation is not required for Advanced Higher.
Students should be able to carry out calculations involving the electric fields due to a system of point charges. Two such calculations are included in the text.
An on-screen exercise is included to give students a visual indication of the electric field around charged particles.

1.6 Extended information

1.6.1 Electric field around a charged conducting sphere

Students should be able to describe the effect of placing a conducting shape in an electric field.

This section offers a further opportunity to carry out experimental work - for example Faraday's ice pail experiment. Whether or not this experimental work can be carried out, an on-screen simulation of the experiment, together with the theory relating to it, is included to enhance students' understanding.

Electrostatic screening and shielding is covered in the notes.

Activity: Faraday's ice pail experiment

This animation shows the ice pail experiment.

It needs to be explained how an electroscope works before students run the animation.

1.6.2 Web links

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Topic 2

Electric potential

2.1 Introduction

This work on electrical potential is broadly similar to the Traditional Advanced Higher Course, although the amount of content has been reduced. For instance, charging by induction is no longer expected.

There are several opportunities for students to perform practical work related to this Topic.

2.2 Potential and electric field

The derivation of the expression $V = Ed$ for a uniform electric field is included in the notes for interest only. It is not examinable. However, students do need to be able to carry out calculations using it, tackling questions similar to the worked example. They should also know that an electric field is a conservative field and be able to explain what this means.

2.3 Electric potential around a point charge and a system of charges

Students should be able to state that the electrostatic potential at a point is the work done by external forces in bringing unit positive charge from infinity to that point.

Students should be able to state that the expression for the electrostatic potential V at a distance r from a point charge Q is $V = \frac{Q}{4\pi\varepsilon_0 r}$.

Students should be able to carry out calculations involving potentials due to point charges.

2.5 Extended information

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Topic 3

Motion in an electric field

3.1 Introduction

This final Topic on Electric fields concentrates on the motion of charged particles in an E-field and considers applications of charged particles and electric fields.

This builds upon the theory of Linear Accelerators covered within the CfE Higher course.

3.2 Energy transformation associated with movement of charge

Students should be able to describe the energy transformation associated with the movement of a charge in an electric field. A worked example is included in the text.

3.3 Motion of charged particles in uniform electric fields

Students should be able to describe the motion of charged particles in uniform electric fields and carry out calculations concerning the motion of charged particles in uniform electric fields. Worked examples are included in the text.

The deflection of an electron beam in an electric field is covered in the text, and also affords the opportunity for some practical work in this area.

3.4 Applications of charged particles and electric fields

Oscilloscope deflecting plates and particle accelerators are outlined here as they are included in the Suggested Learning Activities column of the Course/Unit Support Notes.

The worked example and the student activity entitled Rutherford scattering shows students how to carry out calculations involving the head on collision of a charged particle with a fixed nucleus.

3.4.3 Rutherford scattering

Activity: Rutherford scattering

A straightforward paper-based calculation concerning a Rutherford scattering experiment. The calculation is similar to a worked example given in the notes.

3.5 The electronvolt

Students should be aware that the electronvolt (eV) is as a unit of energy commonly used in high energy particle physics. They should be able to convert between electronvolts and joules.

3.7 Extended information

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Topic 4

Magnetic fields

4.1 Introduction

This topic overlaps with parts of Unit 2 Topic 3 Particles From Space. Therefore, before commencing this topic, it would be beneficial to recap the previous content and to spend some time on the different ways in which magnetic effects can be described.

Much of the topic is similar to the work on magnetic fields covered in the Traditional Advanced Higher course, although some content has been removed. For instance, students are no longer expected to be able to derive the expression for the force per unit length between two parallel current carrying wires at a distance r apart.

4.2 Magnetic forces and fields

The concept of a magnetic field was previously covered in Unit 2. Building upon this, students will now find out about ferromagnetism. As well as allowing students to carry out traditional experiments involving iron filings, compasses or magnetic field plate sets, it may be useful to carry out practical work involving ferrofluids. A ferrofluid is a magnetic liquid which consists of micron size magnetic particles (magnetite) in a mineral oil. When a magnet is brought close to the magnetic particles in the ferrofluid, they move to match the shape of the magnetic field. This provides a three dimensional view of the magnetic field and prevents the misconception that such fields are solely two dimensional. Ferrofluid can be purchased from Mindsets and a video of it in action is also available on their website (http://www.mindsetsonline.co.uk/). Alternatively, magnetic nail polish could be used at this point (http://www.physicscentral.com/explore/action/nailpolish.cfm).

4.3 Magnetic field around a current-carrying conductor

Students studying Physics beyond Advanced Higher level will be expected to work with conventional current. Indeed, the Scottish educational system is almost unique in its use of electron flow for current. Understandably, some teachers may prefer to use conventional current rather than electron flow. However, to be consistent with the CfE Higher Scholar course and to avoid unnecessary confusion at this stage, this topic and all the work in the Advanced Higher Scholar course will use electron flow rather than conventional flow.

Students should be able to define the unit of magnetic induction, the tesla. However, as with all physical quantities, it is good to have a 'feel' for this quantity. Some typical order-of-magnitude values are included, although it should be pointed out that the three largest values given are extreme, and obviously not normally encountered.

Activity: Oersted's experiment

This activity shows the effect of a current in a wire on compass needles. The magnitude and direction of the current in the straight wire can be altered. Questions are included to direct the students' use of the simulation. Students could be asked to draw the field lines around the wire.

The new Advanced Higher course also requires students to be able to draw the magnetic field lines around a solenoid. Though a computer simulation is included here, it is not being suggested that it ought to be used as a substitute for the practical experiment. Indeed, the use of filings or compasses at this point would be considerably more memorable than simulation alone.

4.4 Magnetic induction

Students should be able to state and use the relationship $F = BIl\sin\theta$.

They are not expected to derive this relationship.

Students should already be familiar with the right hand rule, both from the Higher course and Unit 2 - Topic 3 Particles From Space.

4.5 Force on a current-carrying conductor in a magnetic field

Activity: Force on a current-carrying conductor

This interactive simulation demonstrates the force exerted on a current-carrying conductor placed in the field of a horseshoe magnet. This force is sometimes called the 'Lorentz force'.

Activity: Force-on-a-conductor balance

An on-screen simulation to investigate the factors affecting the force on a conductor in a magnetic field.

The simulation is meant to reinforce the actual experiment, not replace it, if possible. Students could be told to plot the graphs of force against current; force against $\sin\theta$; and force against length to show that force is proportional to each of these quantities.

A description of such an experiment to investigate the magnitude of the force on a current carrying conductor in a magnetic field is outlined by SSERC (http://www.sserc.org.uk/index.php/physics-home/advanced-higher/3359-core-experiments).

The exemplification of key areas column of the Advanced Higher Course/ Unit Support Notes suggests the electric motor and the electromagnetic pump as possible applications to consider. Both of these are covered in the notes.

4.5.1 The electric motor

Activity: The simple electric motor

This interactive simulation shows a direct current electric motor in its simplest form.

4.6 The relationship between magnetic induction and distance from a current-carrying conductor

The Hall effect is no longer mentioned in documentation from the SQA and it has therefore not been included in the Scholar course. However, the Suggested Learning Activities column of the Advanced Higher Course/ Unit Support Notes suggests the possible use of a Hall probe to investigate the magnetic induction at a distance from a long current carrying wire. A smartphone or search coil are listed as possible alternatives.

Students should be able to state that the magnetic induction at a perpendicular distance r from an 'infinite' straight conductor carrying a current I is

$$B = \frac{\mu_0 I}{2\pi r}$$

where μ_0 is the permeability of free space. They do not need to derive this expression.

Activity: The hiker

A paper-based exercise in applying the expression for the magnetic field due to a current-carrying conductor. Students should be encouraged to sketch out the situation set in the problem since some basic geometry is required. Students will need to know the value of μ_0 to solve this problem.

This section of work previously included the unification of electricity and magnetism by James Clerk Maxwell and the link between permittivity, permeability and the speed of light. This has now moved to the final topic.

4.7 Comparison of forces

Students ought to be able to compare the strength and range of the gravitational, electrostatic, magnetic and nuclear forces. They also ought to be to provide example of them in action. Highlighting the ways in which the gravitational force is analogous to the electrostatic force provides an opportunity to consolidate Unit 1 and the work already covered in Unit 3. It also paves the way for the final topic on the unification of forces.

4.9 Extended information

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Topic 5

Capacitors

5.1 Introduction

This topic is new to Advanced Higher and it builds upon the work on capacitor charge and discharge covered within the CfE Higher course. It begins with a quick recap of the basics such as the definition of capacitance, the equations for the energy stored by a capacitor and the graphs for capacitor charge and discharge in CR circuits. It then proceeds to introduced new concepts like the time constant and capacitive reactance.

5.2 Revision from Higher

This section allows students to revise the content covered at CfE Higher, which the AH course will build upon. Students would benefit from being provided the opportunity to use data loggers to capture the current-time and potential difference-time graphs for a CR circuit during charging and discharging. The exact mathematical relationships for how the current and p.d. vary with time will be explored in the next section.

Charging a capacitor This activity allows a student to examine the graphs of current and potential difference for a capacitor resistor circuit as the capacitor charges. It also helps students remember that as the potential difference across the capacitor rises the potential difference across the resistor falls. The values for capacitance and resistance can be altered to examine the effect this has on the rate at which the capacitor charges. This can be used either by students individually or with larger groups.

Discharging a capacitor This is a simple activity showing what happens to current from a capacitor as it discharges. It offers a different approach from the animation above for charging capacitors. Again this can be used by students as individuals or with larger groups. Activity: Using the energy stored on a capacitor This short animation illustrates why a charged capacitor is used to power a flashlamp rather than connecting the lamp directly to a battery. This animation can be demonstrated to a class or left to an individual student. The user should first look to see what happens when the lamp is connected to a battery. A capacitor is then charged, and used to power the lamp. A useful discussion to follow up this exercise would involve conservation of energy - how can we get a much brighter flash of light when the capacitor has been charged from the same battery that could only make the bulb glow dimly?

5.3 The time constant for a CR circuit

Students will need to be able to determine the time constant both by numerical methods and by graphical determination.

5.4 Capacitors in a.c. circuits

Before studying the behaviour of capacitors in a.c., it would be helpful to allow students to explore the behaviour of resistors in a.c.

Activity: Resistors in a.c. circuits

This is an interactive activity that allows the student to investigate effect on the alternating current through a resistor as the frequency of the supply is altered. It is not meant to replace the actual experiment, simply to supplement it. If however circumstances dictate that the student cannot be given the chance to carry out the experiment, then this simulation can be used.

This exercise has been designed primarily as an individual activity, although it could be carried out by a small group of students working together, or even as a whole-class activity.

Activity: The capacitor and a.c.

This activity investigates the relationship between frequency and impedance in a capacitive circuit.

This section provides the chance to develop the skills associated with scientific enquiry and practical problem solving, since it allows students the opportunity to form and test a hypothesis. Starting with a class discussion of the capacitive reactance of a capacitor, students could form their own hypothesis, such as that increasing the frequency of an a.c. supply will decrease the capacitive reactance. Candidates could then design their own suitable experiment to test their hypothesis.

5.5 Capacitive reactance

Students will now explore the relationship between current, frequency and capacitive reactance. They will need to be able to apply appropriate relationships to solve problems relating to capacitive reactance, voltage, current, frequency and capacitance.

5.7 Extended information

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Topic 6

Inductors

6.1 Introduction

To understand inductors students will need to be comfortable with the section on magnetic fields (Electromagnetism - Topic 4). They therefore may benefit from reviewing this topic before starting.

Teachers who have taught the Traditional Advanced Higher Course will recognise the work on self-inductance covered in this Topic, as being effectively the same as the self-inductance section contained within the Electrical Phenomena unit of the Traditional CSYS Course.

There are several opportunities for students to perform practical work related to this Topic. Examples include the use of datalogging or waveform capture to determine the self inductance of a coil and experiments to investigate the relationship between current, frequency and inductive reactance.

Since the concept of self-inductance may be somewhat abstract to many students, it may be useful to introduce this Topic with one or two demonstrations of the effects of self-inductance - gradual build-up of current, neon bulb flashing, for example. For those new to teaching Advanced Higher, the necessary experimental setup for this demonstration is described here:

http://www.phys.ufl.edu/demo/5_ElectricityMagnetism/J_Inductance/BackEMF.html

A video explaining the teaching points is available here:

https://www.youtube.com/watch?v=T8O8aTO3ea8

Students should be warned at this stage of the very real dangers of an electric shock from an inductive circuit - even one powered from a 1.5 V cell. This could be used as a lead-in to the work on the energy stored in an inductor.

6.2 Magnetic flux and induced e.m.f.

Although students do not need to know the terms magnetic flux and magnetic induction, the concept of magnetic flux is the best starting point for a treatment and understanding of self inductance. The relevant Content Statements say that students should be able to state that an e.m.f. is induced across a coil when the current through the coil is varying, and that they should be able to explain the production of the induced e.m.f. across a coil.

The work of Lenz and Faraday is combined in the notes in the relationship $\varepsilon \propto -\frac{d\phi}{dt}$.

This allows students to explain the direction of the induced e.m.f. in terms of energy.

An excellent demonstration of Lenz's Law and eddy currents is outlined on the following SSERC website:

http://www.sserc.org.uk/index.php/physics-home/advanced-higher/3359-core-experiments

It involves dropping a steel ball bearing down a copper tube and comparing the time taken to reach the bottom to that of a neodymium magnet. It can be explained that the neodymium magnet takes substantially longer to fall since it places the copper tube in a changing magnetic field, inducing a current in the copper tube. This current creates its own magnetic field, which opposes the magnetic field that created it.

The following SSERC site contains a document entitled The Art of Induction:

http://www.sserc.org.uk/index.php/physics-home/advanced-higher/3362-investigation-ideas

It details a possible student investigation to examine the factors affecting the voltage induced across a coil by a moving magnet. The whole document is therefore too lengthy for a single class practical, but the first experiment would allow an exploration of the important features of Lenz's law. It would prompt a discussion based around the fact the e.m.f. is negative as the magnet moves into the coil and then becomes positive as the magnet leaves. The following webpage suggests a slightly different setup, but also uses dataloggers to teach Lenz's law:

http://www.nuffieldfoundation.org/practical-physics/datalogging-electromagnetic-induction

Details of numerous experiments associated with this topic are also available from the IOP (tap.iop.org/fields/electromagnetism/414/file_46953.doc).

6.3 Eddy currents

Applications of eddy currents that are dealt with include: electromagnetic braking, induction heating, metal detectors and the levitation of superconductors. Some of these applications are mentioned in the Course/ Unit Support Notes for Advanced Higher. Others go beyond but are included for completeness.

6.4 Inductors and self-inductance

Students should be able to state that the self-induced e.m.f. in a coil is $\varepsilon = -L\frac{dI}{dt}$.

where L is the self-inductance of the coil. They should also be able to define the unit of inductance, the henry, from this relationship. It should be pointed out to students that the minus sign in this expression is as a result of Lenz's law, and is the reason for the induced e.m.f. being known as a back e.m.f.

Students should be able to explain that the work done in building up the current in an inductor is stored in the magnetic field of the inductor and that the energy stored in the magnetic field of an inductor may be a source of e.m.f. These are difficult ideas for students to grasp and may be illustrated by means of some of the simple experiments already mentioned.

Students should be able to state that the energy stored in an inductor is $\frac{1}{2}LI^2$ and carry out calculations involving this relationship. The derivation of this relationship is included in the notes, although students are not expected to learn this derivation. A worked example on the use of this relationship is also included in the notes.

6.5 Inductors in d.c. circuits

Students should be able to sketch qualitative graphs of the growth and decay of current in d.c. circuits containing an inductor. These graphs, along with an explanation of how they arise, are included in the notes.

A neon bulb being lit by the back e.m.f. in an inductive circuit powered from a 1.5 V cell is covered in the notes. This should be demonstrated to students if possible, rather than simply relying on the notes. Details are mentioned in section 6.1 of this guide.

Inductors in certain applications are known as chokes (because of their ability to 'choke' or oppose the build-up of current). Two of these applications are covered - the inductor as a high frequency filter in a radio circuit and the choke that is included in the circuit for a fluorescent tube.

Students should be familiar with the principles of a method to illustrate the growth of current in a d.c. circuit. Two methods are described in the notes. It is suggested that these descriptions be backed up by actual experimental work. It might be appropriate to demonstrate the gradual build-up of current in a large value inductor, using a suitable analogue meter, and follow up this demonstration with a student experiment using a suitable data-capture device. Either of these methods would enable students to calculate the self-inductance of the coil used, from an analysis of the graph of current growth. The back e.m.f. generated across the inductor at the moment of switch-on is equal and opposite to the e.m.f. of the supply.

The gradient of the current-time graph, at t = 0, is calculated and used in the expression $L = \left[\frac{E}{dI/dt}\right]_{t=0}$, where E is the e.m.f. of the supply.

The following manufacturer provides preassembled kits to simplify investigations into the growth and decay of current in a d.c. circuit containing an inductor:

http://www.djb.co.uk/ppe_ind_investigations.html

6.6 Inductors in a.c. circuits

Students need to be able to use the equation for the reactance of an inductor and explain its significance.

The dependence of inductive reactance on frequency is the basis of some functions of inductors - as low-pass filters and for removing high frequency noise and spikes from signals. They should also be able to compare the frequency dependence of capacitive reactances to that of inductive reactances.

A description of a suitable method to show how the current varies with frequency in an inductive circuit is included in the notes, but, again, students should be given the opportunity to carry out the experimental work, if at all possible.

6.8 Extended information

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6.8.1 Levitation of superconductors

Activity: Levitating superconductor

This short video clip shows a demonstration of magnetic levitation. A piece of superconductor, cooled with liquid nitrogen, is suspended above a permanent magnet.

Topic 7

Electromagnetic radiation

7.1 Introduction

This very short topic is primarily new to Advanced Higher, but much of the content does have commonalities with work from Unit 2 of the Traditional course.

7.2 The unification of electricity and magnetism

The unification of electricity and magnetism was previously only mentioned in the 'Contexts, Applications, Illustrations and Activities' column of the Arrangements document of the Traditional course. Whereas, it is now a mandatory course key area within the CfE Advanced Higher Course/ Unit Support Notes. The deeper implications of this work may not be appropriate for some students, but as a starter activity, teachers may wish to introduce the section with a quick clip from Brian Cox outlining the significance of Maxwell's work:

https://www.youtube.com/watch?v=uYz_kQ7UkY8

7.3 The wave properties of em radiation

This section potentially provides an opportunity to revise the physics of travelling waves, electric field strength and magnetic induction.

7.4 Permittivity, permeability and the speed of light

As it was previously mentioned in the Contexts, Applications, Illustrations and Activities within the Traditional Advanced Higher arrangements document, many teachers have always taught the relationship between the permittivity and permeability of free space and the speed of light. This is now a mandatory area within the CfE course/ unit support notes and the formula $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ has been added to the Relationships sheet.

As mentioned in the Course/ Unit Support notes, students would benefit from an opportunity to estimate the speed of light by carrying out an experiment to determine permittivity of free space using a parallel plate capacitor and determining permeability of free space using a current balance. A description of the parallel plate capacitor experiment is available from PASCO(ftp://ftp.pasco.com/support/Documents/English/EX/EX-9985-220/Capacitance.docx).

The current balance experiment is outlined by (http://www.ph.surrey.ac.uk/UserFiles/File/Microsoft%20Word%20-%20Autumn_Classical_Current%20balance). However, this equipment is rare in schools.

7.6 Extended information

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